Lattice QCD Campaign

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LQCD group & collaborators

JEFFERSON LAB

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MESON SPECTRUM

PRL103 262001 (2009) $I=1$
PRD82 034508 (2010) $I=1,\ K^\star$
PRD83 111502 (2011) $I=0$
JHEP07 126 (2011) $c\bar{c}$
PRD88 094505 (2013) $I=0$
JHEP05 021 (2013) $D,\ D_s$

BARYON SPECTRUM

PRD84 074508 (2011) $(N,\Delta)^\star$
PRD85 054016 (2012) $(N,\Delta)_{\text{hyb}}$
PRD87 054506 (2013) $(N\ldots\Xi)^\star$
PRD90 074504 (2014) $\Omega^\star_{ccc}$
PRD91 094502 (2015) $\Xi^\star_{cc}$

HADRON SCATTERING

PRD83 071504 (2011) $\pi\pi\ I=2$
PRD86 034031 (2012) $\pi\pi\ I=2$
PRD87 034505 (2013) $\pi\pi\ I=1,\ \rho$
PRL113 182001 (2014) $\pi K, \eta K$
PRD91 054008 (2015) $\pi K, \eta K$
ARXIV: 1507.02599 $\pi\pi\ I=1,\ \rho$

NUCLEI

PRD87 034506 (2013)
PRD90 094507 (2014)
PRL113 25001 (2014)
PRD91 114503 (2015)
ARXIV: 1506.05518
ARXIV: 1505.02411

DISTRIBUTIONS

PRD91 074513 (2015) OPE

"TECHNOLOGY"

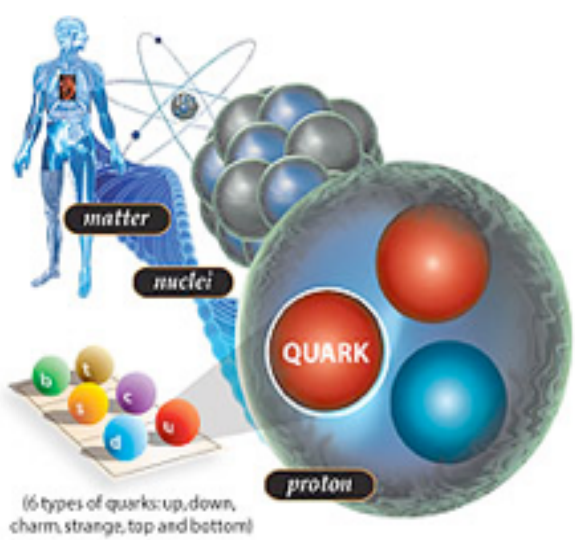
PRD79 034502 (2009) lattices
PRD80 054506 (2009) distillation
PRD85 014507 (2012) $\vec{p}>0$

MATRIX ELEMENTS

PRD91 114501 (2015) $M' \to \gamma M$
PRD90 014511 (2014) $f_{\pi^\star}$

Introduction

- Believe fundamental building blocks of matter are ***quarks*** bound by ***gluons***, via ***strong nuclear force***.
- Quantum Chromodynamics (QCD) - theory which describes the strong interactions
- Understanding how quarks and gluons constitute matter under QCD is a major expt. goal
  - < ~20% of proton mass comes from mass of the quarks, rest comes from glue
  - gluon self-coupling and gluon excitations can create ***exotic forms of matter***



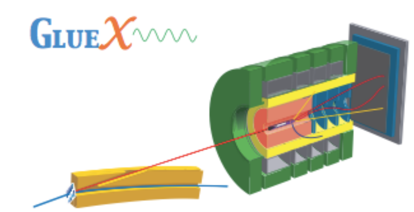
GlueX in the new Hall-D of Jefferson Lab@12 GeV. Hunting for exotics!

Jefferson Lab

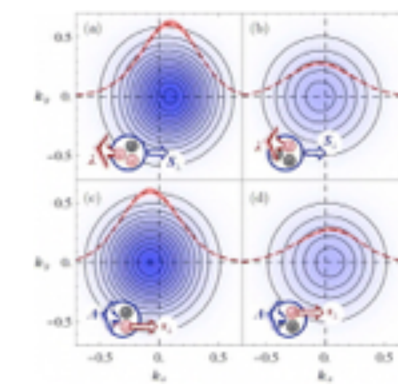
Brookhaven National Lab

Questions in Nuclear Physics

- What observable states does QCD allow?
  - What is the role of the gluons? What about exotic matter?
  - Focus of GlueX experiment

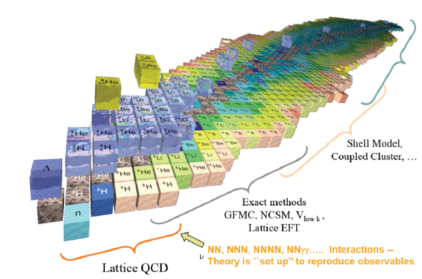


- How do nucleons arise?
  - how are quarks & gluons distributed in a proton or neutron?
  - Focus of JLab 12 GeV, Halls A, B & C, RHIC-spin and future EIC

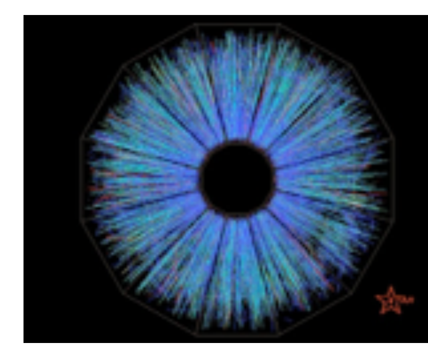


Hägler, Musch, Negele, Schäfer, EPL 88 61001

- QCD must predict properties of light nuclei
  - predict nuclear reaction properties, connect to effective theories
  - $730M Facility for Rare Isotope Beam (FRIB) will investigate nuclear structure and interactions



- How does QCD behave under extreme temperatures & pressures such as in supernovae or shortly after Big-Bang
  - Studied in RHIC at BNL



USQCD National Effort

US Lattice QCD coordinated effort involving JLab, BNL & FNAL

USQCD Exec. Comm.

USQCD Sci. Prog. Comm.

Science campaigns:

HEP	Intensity Frontier Energy Frontier
NP	Cold nuclear physics Thermodynamics

USQCD Facilities:

2010 - 2014: LQCD ext: $18M
2009 - 2012: LQCD ARRA: $5M
〉 *$23M*

2015 - 2019: LQCD ext-II: *$14M*

Leadership Comp. Facilities:

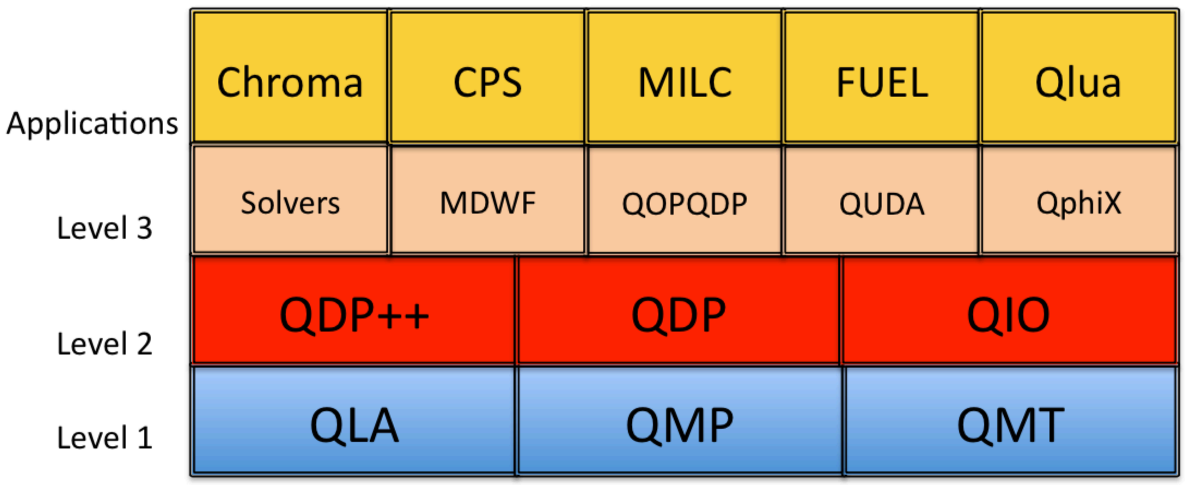
Proposals to DOE + NSF programs
Resources: ORNL, ANL, NERSC, NSF

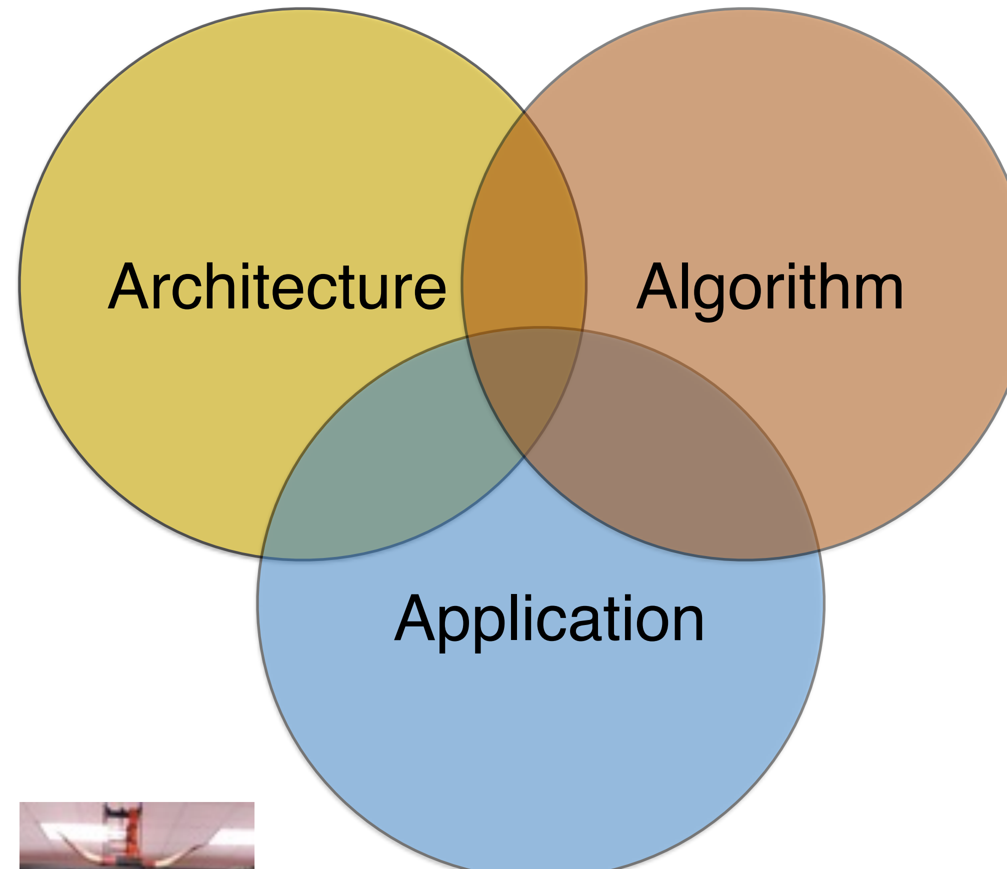
Software:

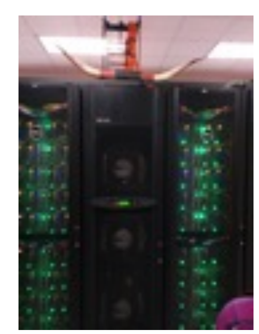
2001 - 2012: SciDAC I & II
2013 - 2016: HEP + ASCR SciDAC
2013 - 2016: NP + ASCR SciDAC
JLab portion: $1.6M NP + $0.88M ASCR

SciDAC

LQCD software development effort to support Leadership Computing and USQCD facilities







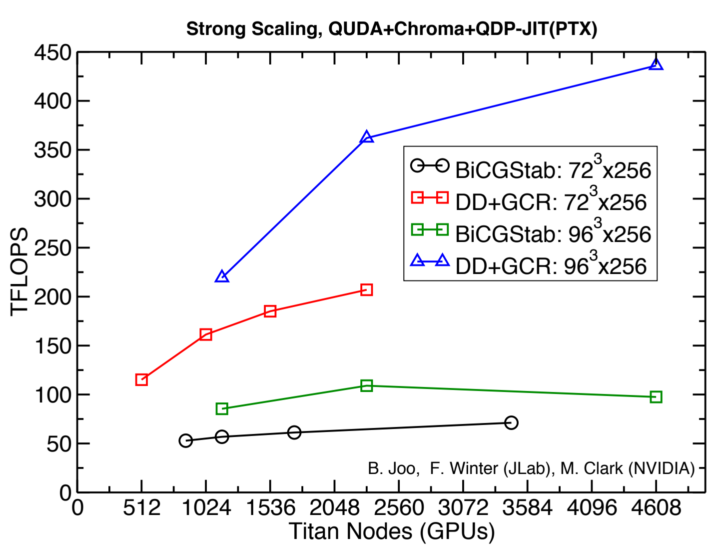
JLab: Jie Chen, Balint Joo, Frank Winter

Many computing architectures

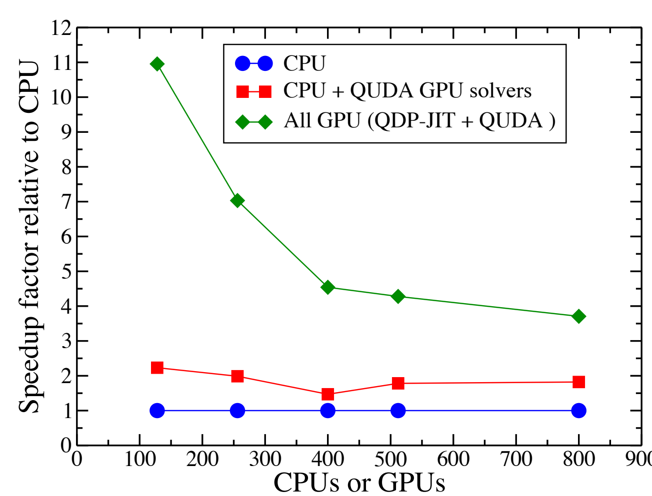
- Opportunity to optimize for speed & cost
  - Current & future leadership "*capability*" resources - gauge generation
  - USQCD "*capacity*" resources - propagators & contractions

- JLab has been at forefront of these developments
  - NviDIA GPUs (B. Joo, F. Winter + NviDIA developers)
  - Intel Many Core (Xeon Phi) (B. Joo, C. Watson + Intel Parallel Computing Labs)
  - BlueGene/Q (F. Winter + ANL staff)
  - Partnership with SciDAC Super Institute - "automatic" porting of code

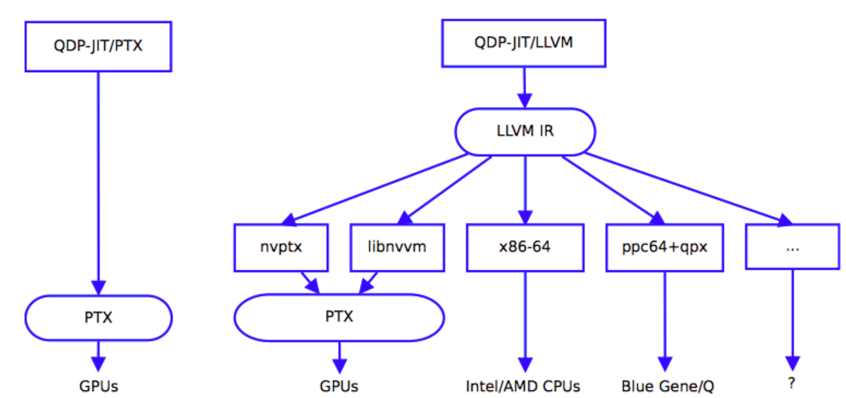
Propagator speed
Titan (K20X)



Gauge generation speedups
Titan (K20X)



Porting code: Just-In-Time compilation
Domain specific language



JLab + SciDAC Super Institute

Lattice QCD

- First-principles numerical approach to the field-theory
  - Evaluate **correlation functions** e.g $\int \mathcal{D}\psi \mathcal{D}\bar{\psi} \mathcal{D}A_\mu \; \bar{\psi}\Gamma\psi(t)\,\bar{\psi}\Gamma\psi(0) \; e^{-\int d^4x\,\mathcal{L}_{\text{QCD}}(\psi,\bar{\psi},A_\mu)}$

    'sum 'field 'probability

    via **Monte-Carlo** sampling of path-integral

    on a **finite cubic grid**

    - » in principle recover physical QCD as

      $$a \to 0 \qquad L \to \infty$$

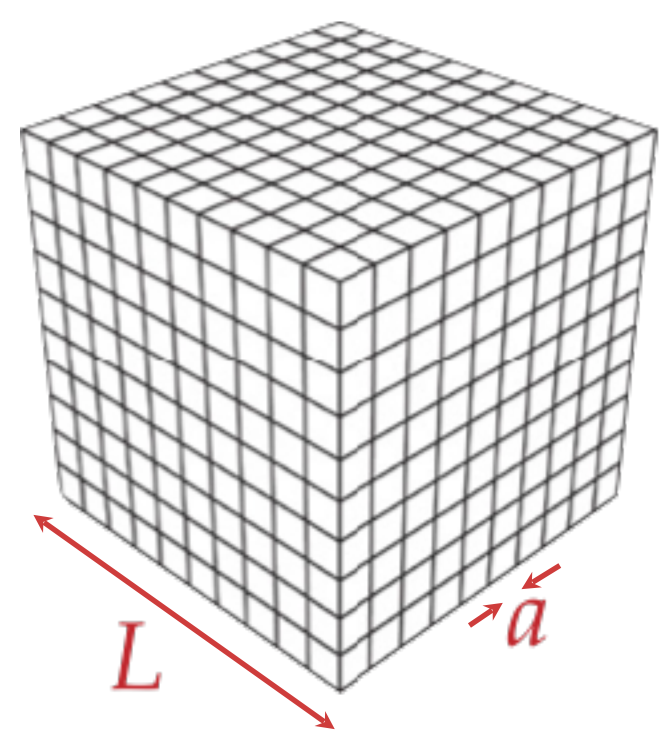
      However, use finite *L* as a tool (see R. Briceno talk)

    - » practical calculations often use

      $$m_q^{\text{calc.}} > m_q^{\text{phys.}}$$

    - » large scale computational problem ...

CUBIC LATTICE

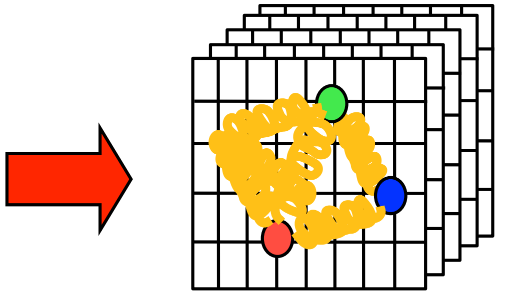


LQCD workflow

LQCD workflow

Generate the configurations

- Leadership level
- 60K cores, 10's TF-yr



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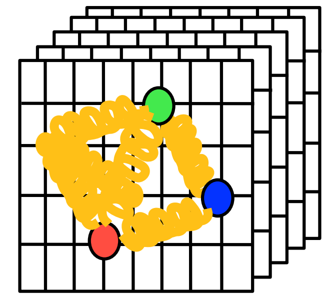
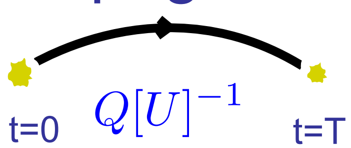


+

Analyze
100K copies
4 Kepler GPUs
Now also AMG!

Propagators



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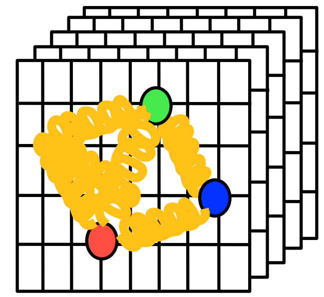

Analyze

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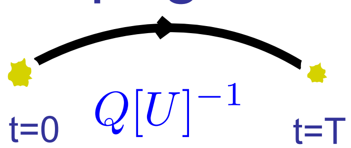
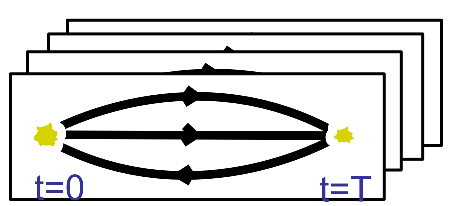


Contract

- 8 cores, CPUs

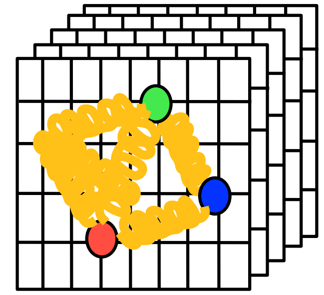
Correlators

100K – 1M copies



LQCD workflow

Generate the configurations
- Leadership level
- 60K cores, 10's TF-yr



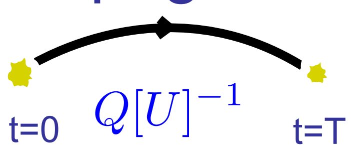
Analyze
100K copies

4 Kepler GPUs

Now also AMG!

+

Propagators



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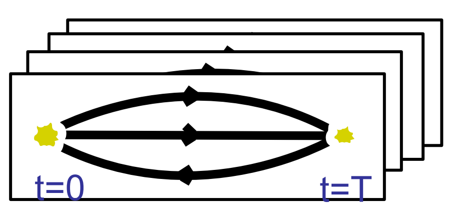

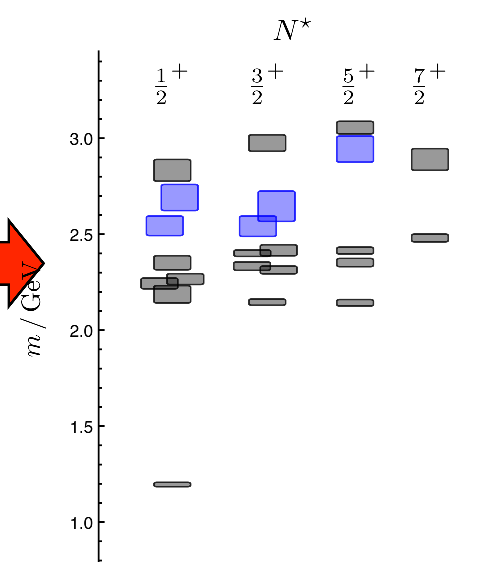

LQCD workflow

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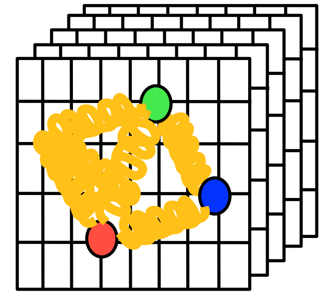
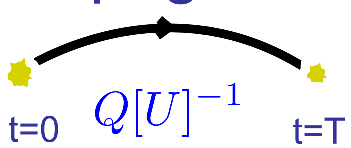


Few big jobs
Few big files

Propagators

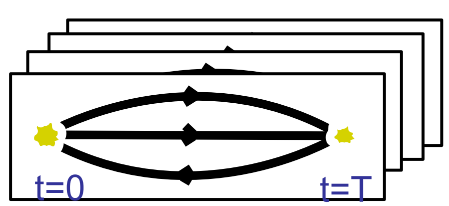


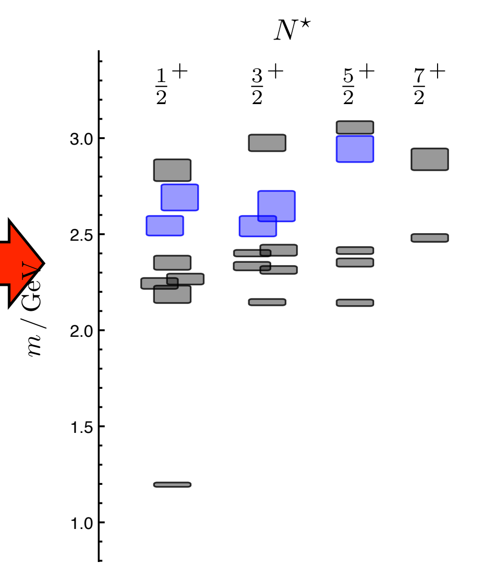
+

Analyze
100K copies
4 Kepler GPUs
Now also AMG!

Contract
- 8 cores, CPUs

Correlators
100K – 1M copies



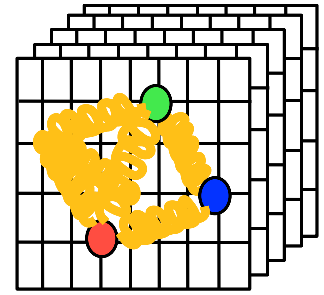


Many small jobs
Many big files

I/O movement

LQCD workflow

Generate the configurations
- Leadership level
- 60K cores, 10's TF-yr



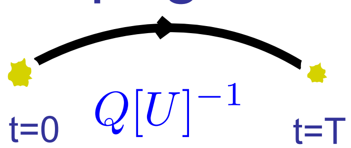
~25%
Leadership level

Analyze
100K copies
4 Kepler GPUs
Now also AMG!

+

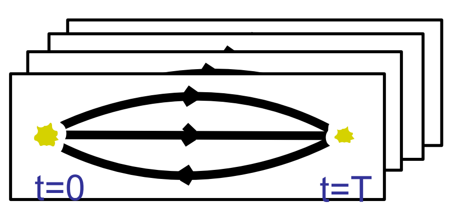
~75%
Throughput mode

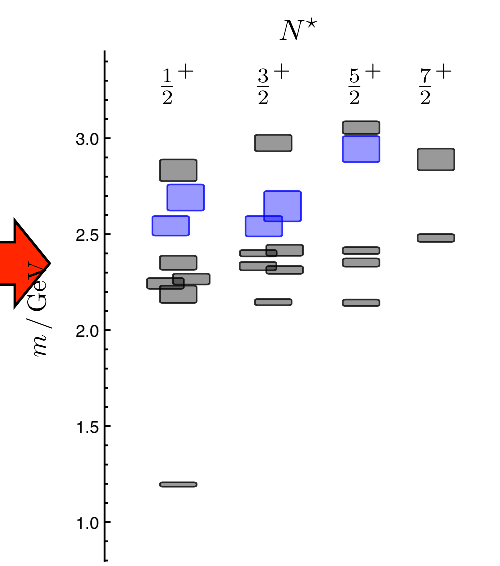
Propagators



Contract
- 8 cores, CPUs

Correlators
100K – 1M copies





> 5%
New analysis cost

Leadership facilities & USQCD facilities

- Leadership resources - ***capability***
  - Systems essential for USQCD gauge generation program
  - Networks + compute nodes designed to support large node count jobs
    - ➡ Titan: exchange rate is 20M core-hours for $1M in integrated cost of project
  - DOE + NSF programs (INCITE, ALCC, Petascale) available for high profile critical applications
    - USQCD and associated projects quite successful
    - Highlight: JLab spectroscopy project: 250M core-hour project still largest award to date @ ORNL

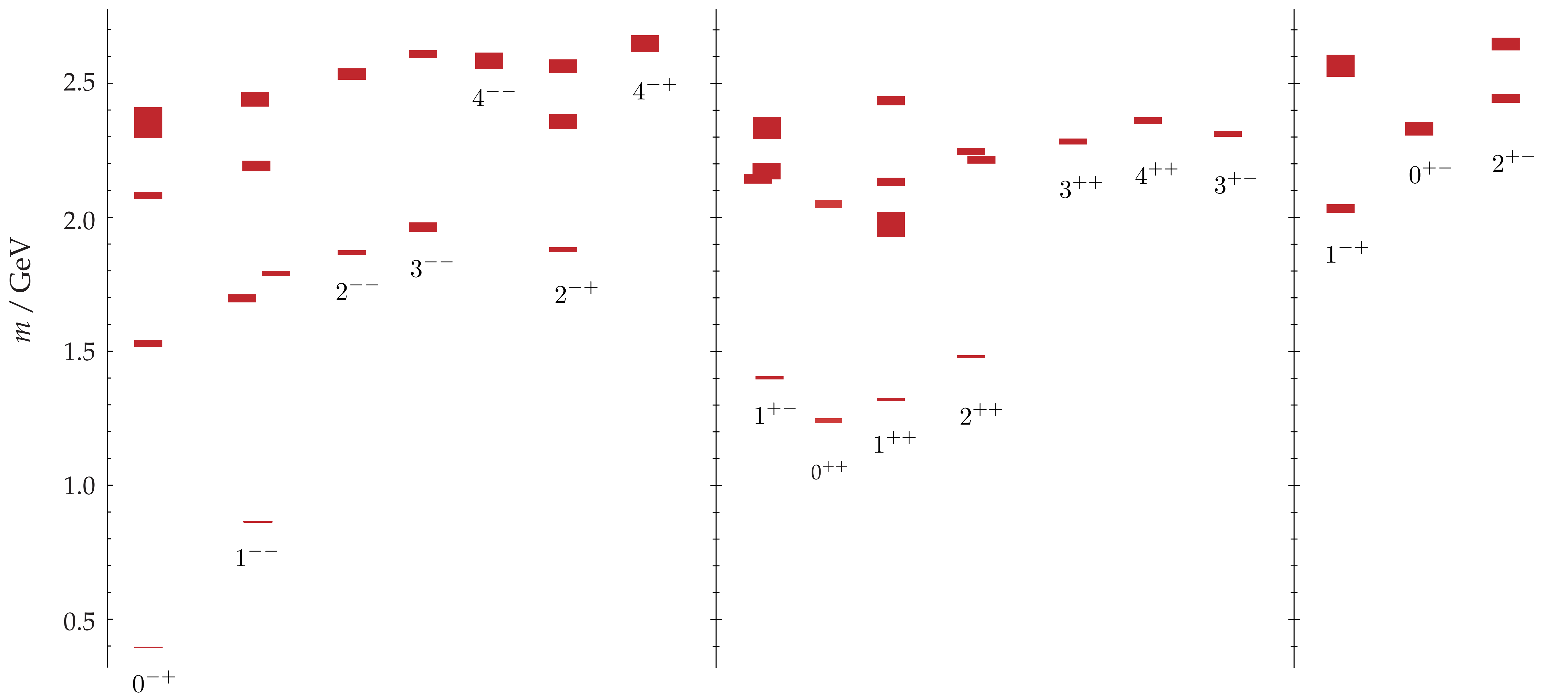
- USQCD resources - ***capacity***
  - Provide essential leverage of capability resources
  - Systems cost optimized for USQCD physics program
    - SciDAC essential to exploit new computing architectures
  - Virtuous circle - success at optimizing enables optimal use of future leadership systems

- JLab:
  - Improving energy efficiency of computing center - part of $27M DOE project
    - Increasing power & cooling to support future growth in LQCD & 12GeV program
  - Developing resource sharing between Expt. Phys. & LQCD for increased utilization

Spectroscopy: isovector meson spectrum

- Appears to be some $q\bar{q}$-like near-degeneracy patterns

$m_\pi \sim 391\,\mathrm{MeV}$



PRL 103; PRD 82, 88

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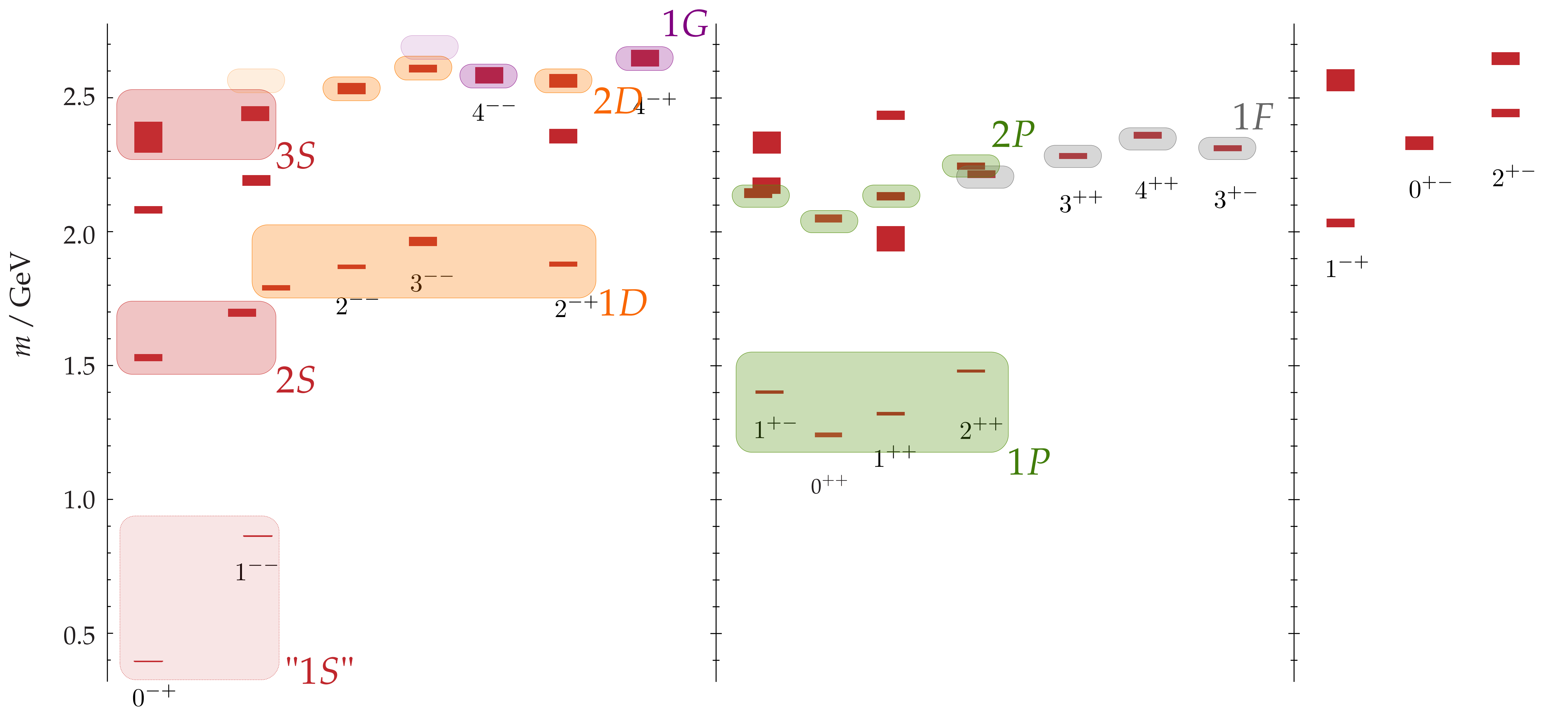
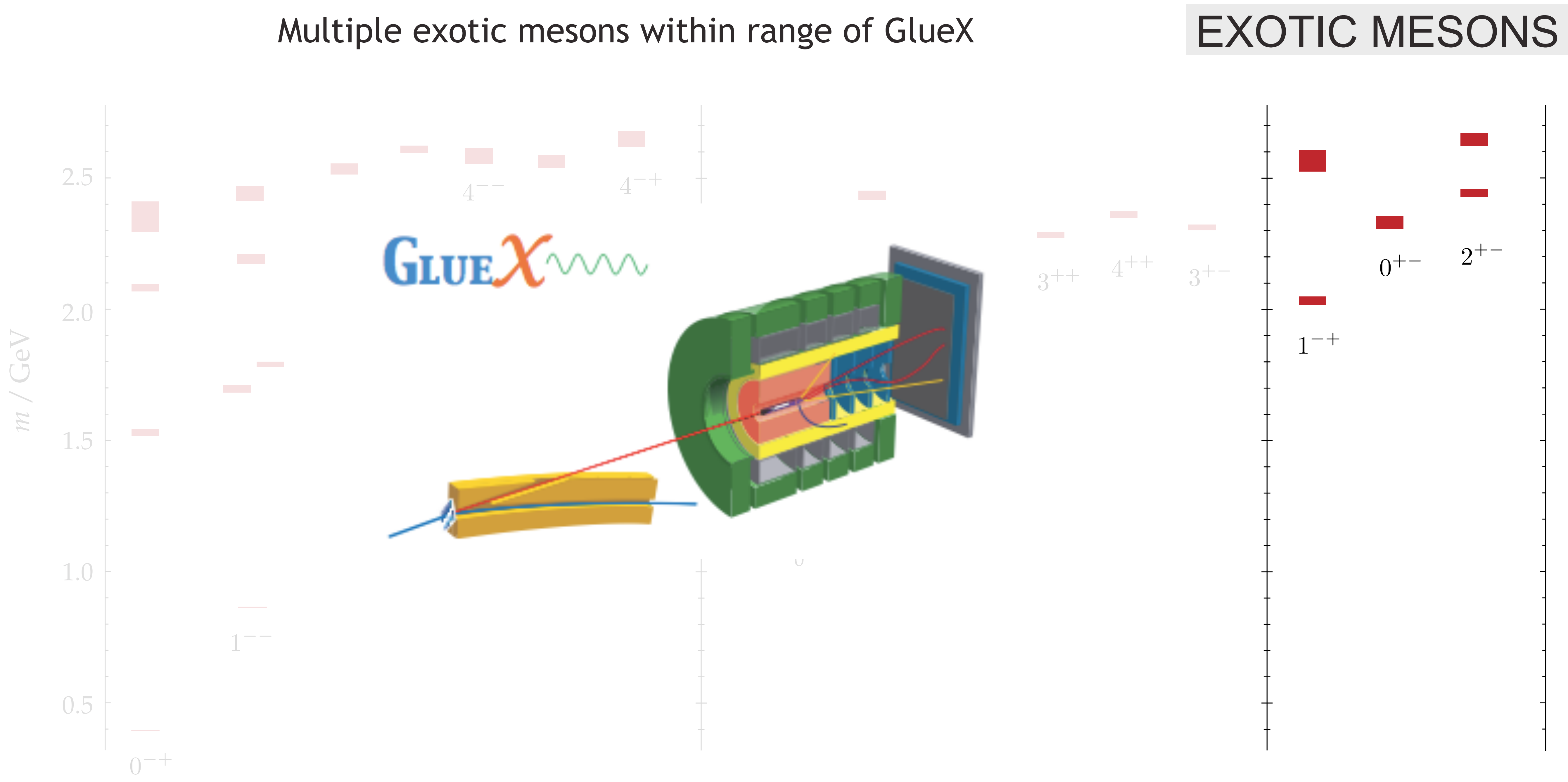


PRL 103; PRD 82, 88

Meson spectrum from lattice QCD

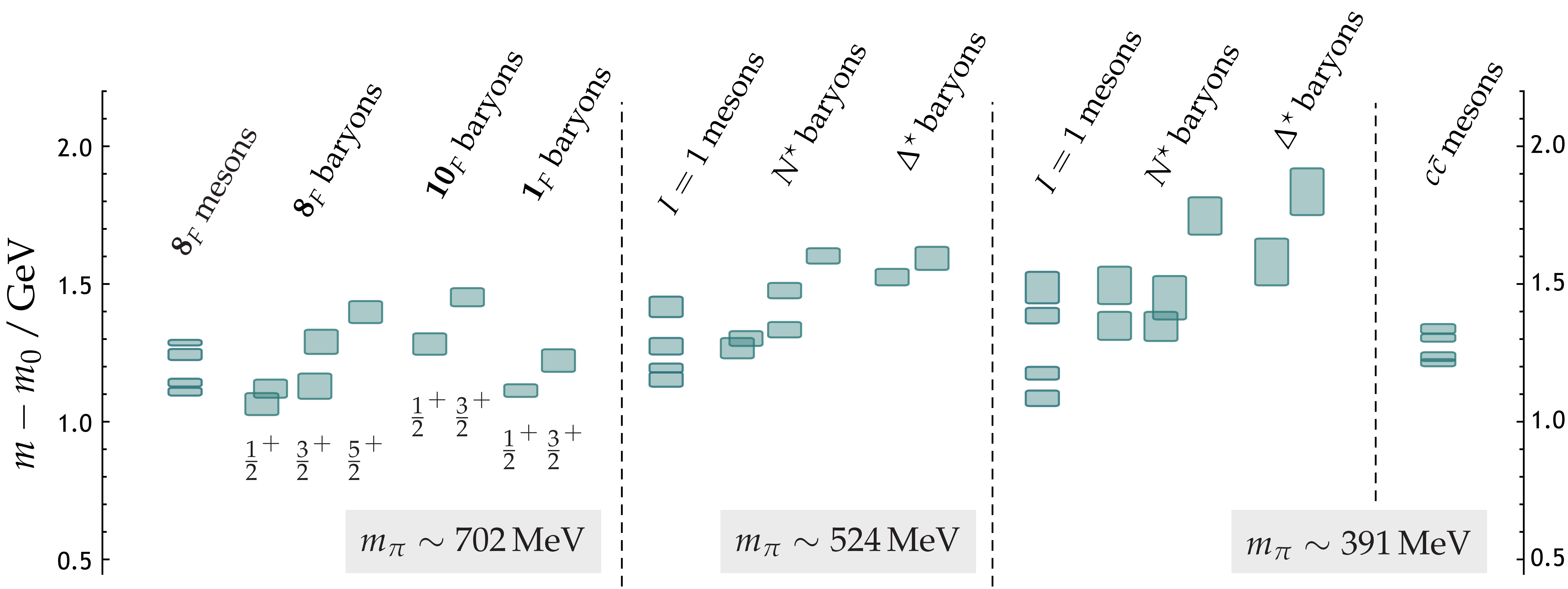
Multiple exotic mesons within range of GlueX



PRL 103; PRD 82, 88

Chromo-magnetic excitation

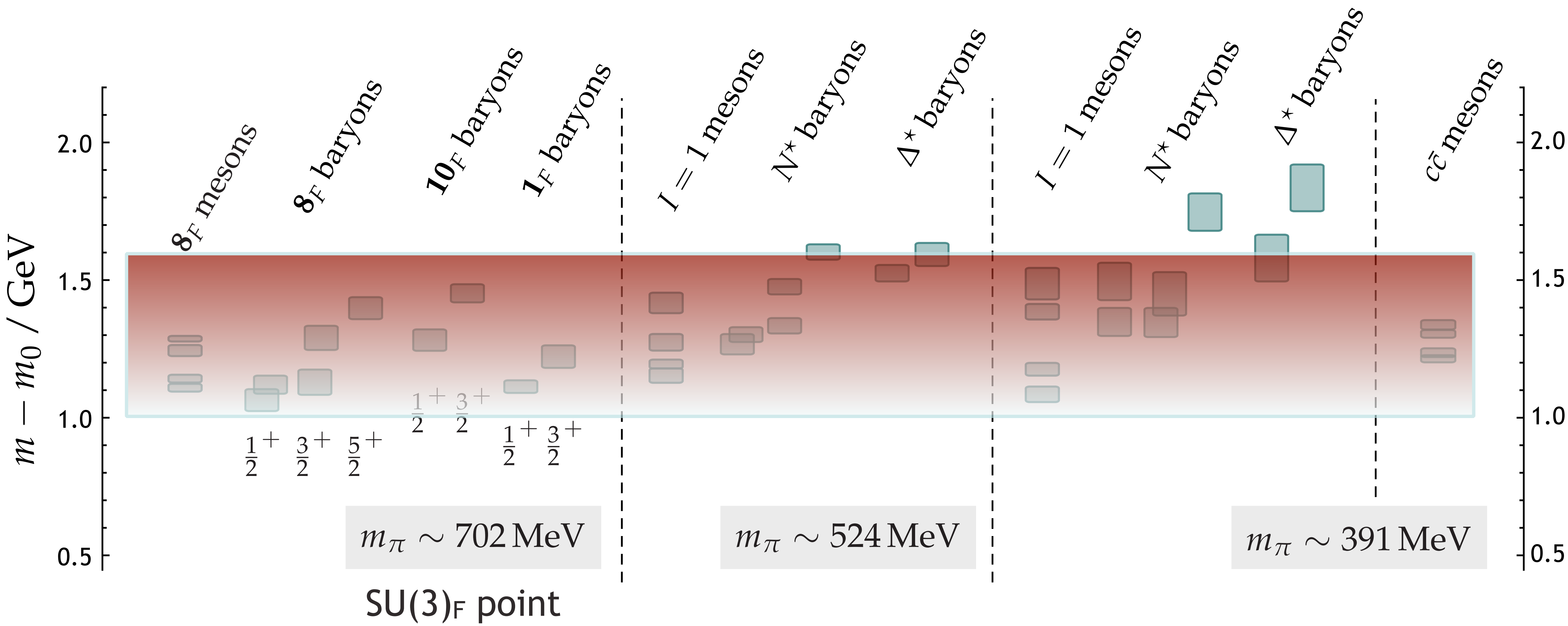
- Subtract the 'quark mass' contribution



SU(3)F point

Chromo-magnetic excitation

- Subtract the 'quark mass' contribution



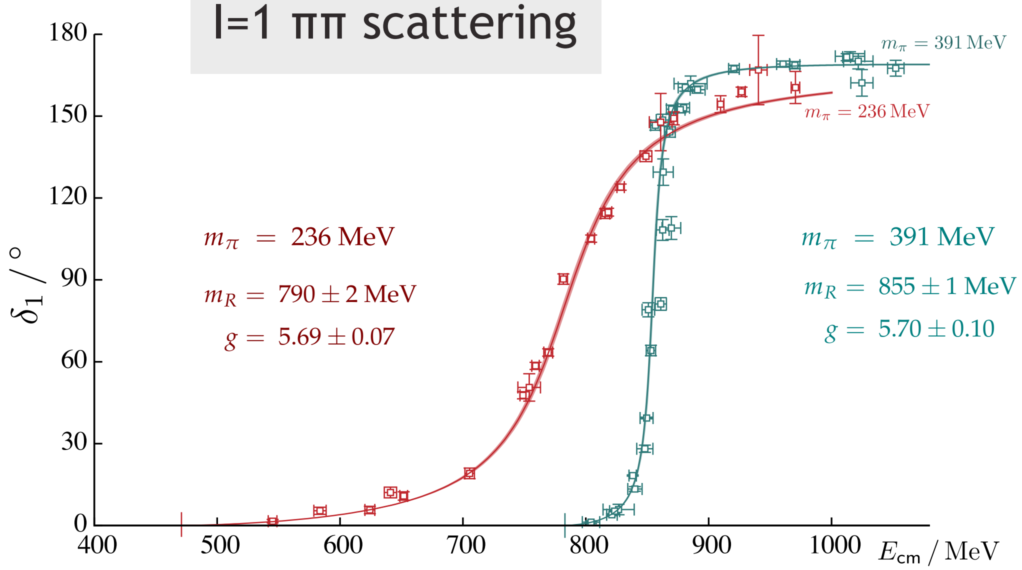
– ***Common energy scale of gluonic excitation*** $\sim 1.3\,\mathrm{GeV}$

Spectroscopy

- First glimpse of spectrum of QCD light quark, strange quark, and charm quark mesons & baryons
- Results suggest rich pattern of states similar to non-rel. quark model + gluonic excitations
  - Possibly many states within energy range of GlueX
- Expt. verification requires measurement in many decay channels
  - Need partial wave couplings and resonance parameters

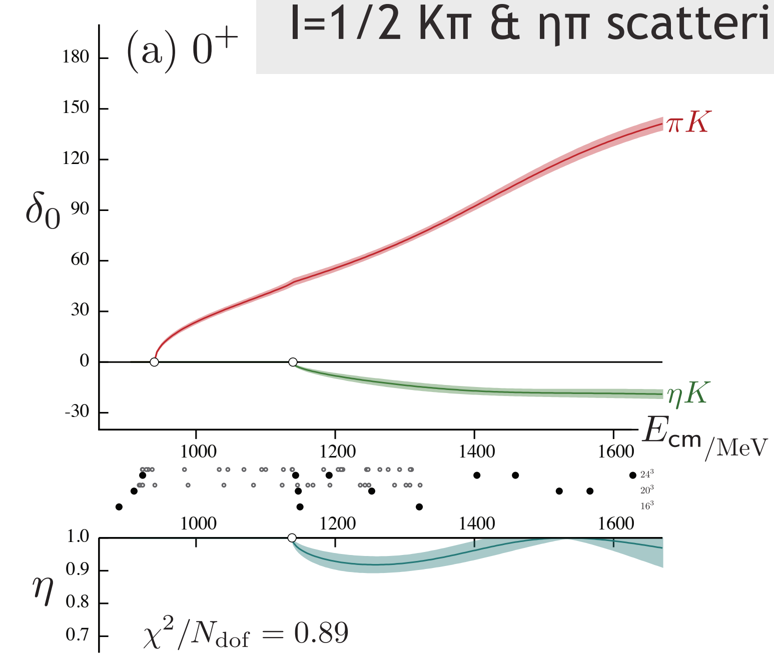
I=1 ππ scattering

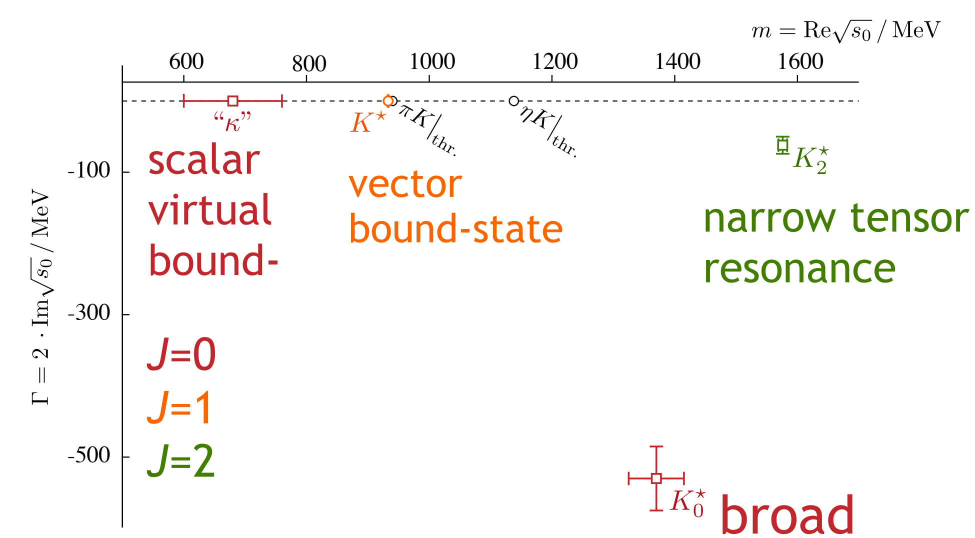
First result from ALCC



I=1/2 Kπ & ηπ scattering

$m_\pi \sim 391$ MeV





- First LQCD determination of coupled channel resonance
- Interesting observations about scalar sector
- Stepping stone to compute exotic meson parameters

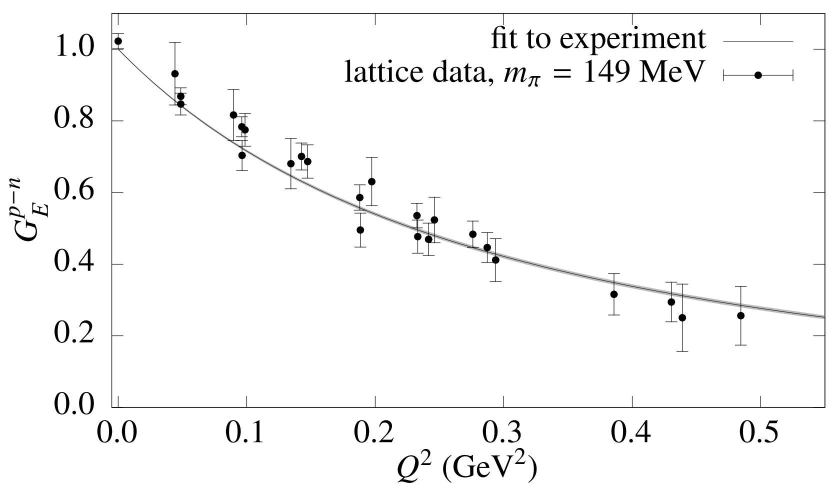
PRL 113 182001
PRD 91 054008
1507.02599

Hadron Structure

- LHPC: calc. @ m_π=149 MeV showing ***isovector*** $G_E(Q^2)$ and $G_M(Q^2)$ agree with expt. error band
  - Needed is the isoscalar contribution
- First calculation of disc. light quark contributions to EM form factors: ~0.5% of connected result
- Strange EM form factors consistent with expt. and much smaller uncertainty
  - ***Hierarchical Probing*** proved crucial to reduce noise by 10x and resolve the signal
- Challenge: to control systematic errors sufficiently to resolve proton radius puzzle

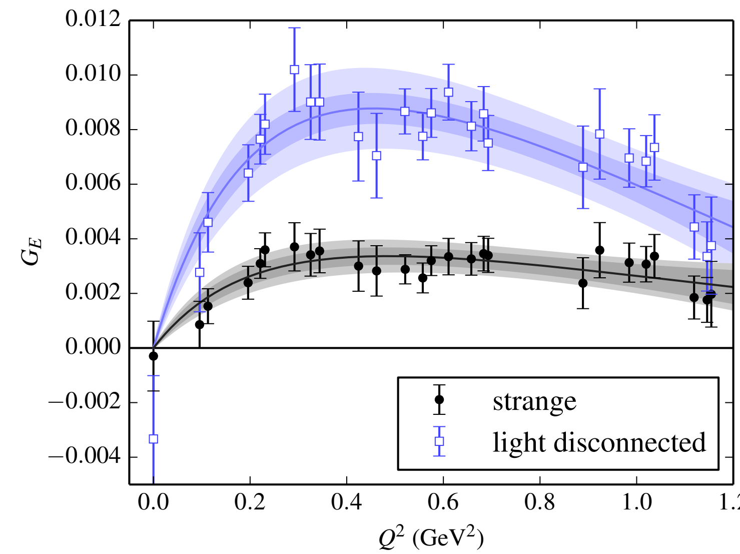
LHPC

Electromagnetic Form Factor

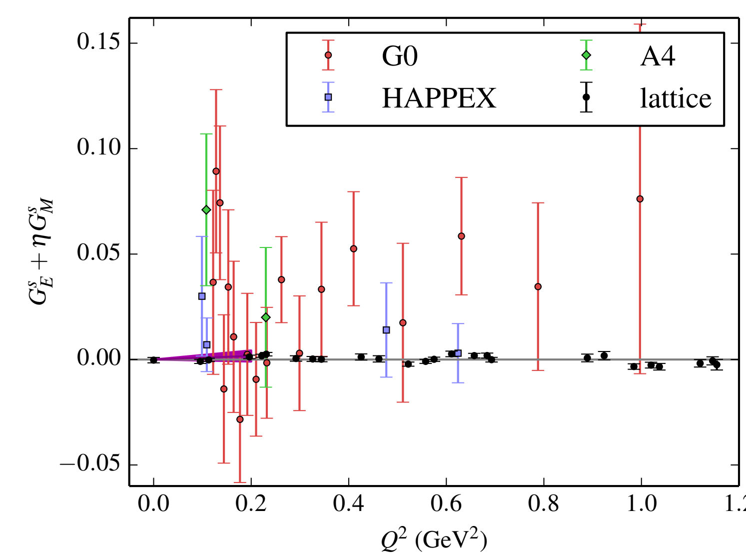


$m_\pi = 317$ MeV

Disconnected contribution to G_E



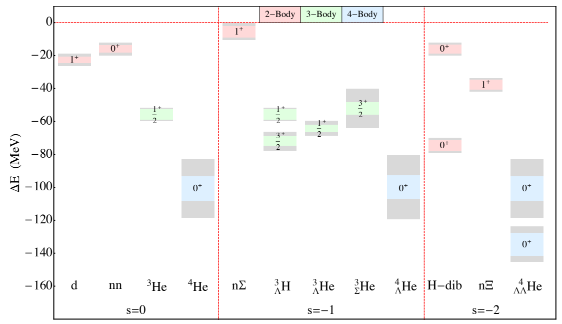
Disconnected contribution to G_E



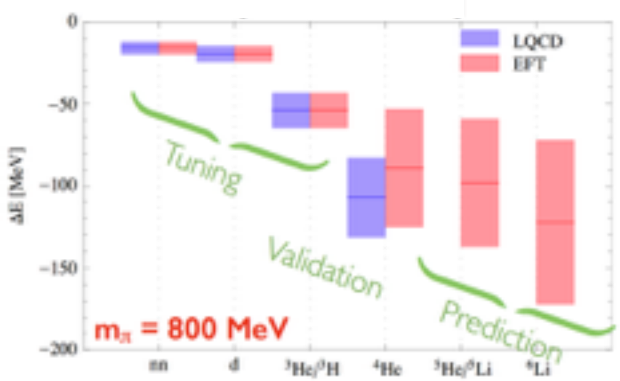
» S. Syritsyn will join JLab as a Nathan Isgur Fellow this fall

Orginos, Syritsyn + LHPC: 1404.4029, 1505.01803

Nuclear structure



Nuclear Structure



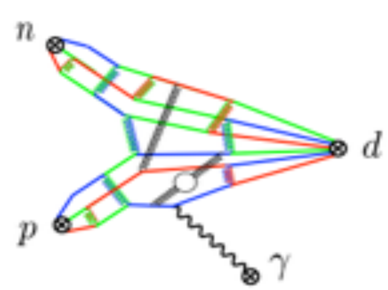
Refining Nuclear Forces

The binding of light nuclei and their properties

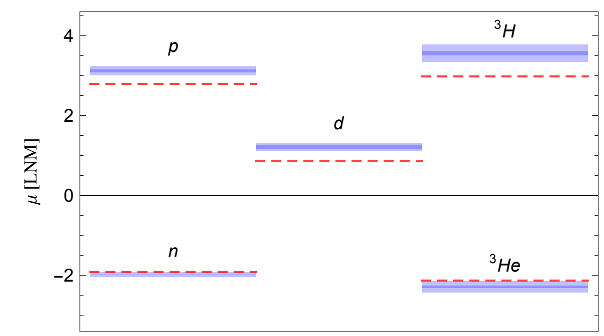
- Binding of light nuclei
  - Used to predict properties of larger nuclei through matching to Nuclear EFT
- First calculations of an inelastic nuclear reaction (neutron capture cross section)
- First calculations of the magnetic moments and polarizabilities of light nuclei

➡ Nuclear shell-model structure of light nuclei persists over range of quark masses

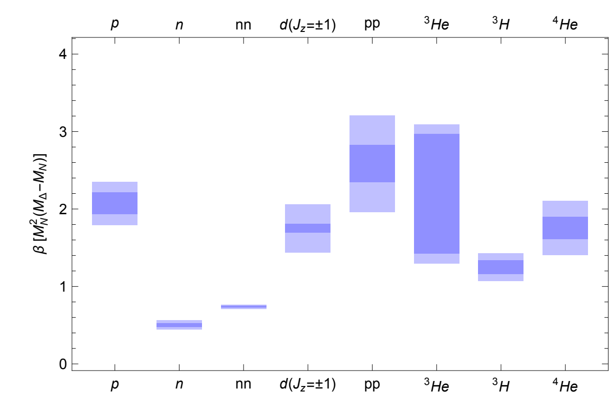
➡ Magnetic moments of nucleons are generically quark-model



Nuclear Reactions



Magnetic Moments



Nuclear Polarizabilities

Near Future Program:

- Properties of multi-neutron systems and the three-body forces
- Axial couplings for neutrino int. with nuclei
- Refinement of nuclear shell-model calculations of double beta-decay rates
- Nuclei and exotic nuclei at lighter pion masses

Orginos & NPLQCD: 1206.5219, 1301.5790, 1409.3356, 1505.02422, 1506.05518

Involvement with experimental program

Physics Opportunities with the 12 GeV Upgrade at Jefferson Lab

Jozef Dudek, Rolf Ent, Rouven Essig, Krishna Kumar, Curtis Meyer, Robert McKeown, Zein Eddine Meziani, Gerald A. Miller, Michael Pennington, David Richards, Larry Weinstein, Glenn Young

Second phase of GlueX program with BaBar DIRC-s (approved)

A study of decays to strange final states with GlueX in Hall D using components of the BaBar DIRC

(A proposal to the 42nd Jefferson Lab Program Advisory Committee)

M. Dugger,[1] B. Ritchie,[1] I. Senderovich,[1] E. Anassontzis,[2] P. Ioannou,[2] C. Kourkoumeli,[2] G. Vasileiadis,[2] G. Voulgaris,[2] N. Jarvis,[3] W. Levine,[3] P. Mattione,[3] W. McGinley,[3] C. A. Meyer,[3] R. Schumacher,[3] M. Staib,[3] F. Klein,[4] D. Sober,[4] N. Sparks,[4] N. Walford,[4] D. Doughty,[5] A. Barnes,[6] R. Jones,[6] J. McIntyre,[6] F. Mokaya,[6] B. Pratt,[6] W. Boeglin,[7] L. Guo,[7] E. Pooser,[7] J. Reinhold,[7] H. Al Ghoul,[8] V. Crede,[8] P. Eugenio,[8] A. Ostrovidov,[8] A. Tsaris,[8] D. Ireland,[9] K. Livingston,[9] D. Bennett,[10] J. Bennett,[10] J. Frye,[10] M. Lara,[10] J. Leckey,[10] R. Mitchell,[10] K. Moriya,[10] M. R. Shepherd,[10] O. Chernyshov,[11] A. Dolgolenko,[11] A. Gerasimov,[11] V. Goryachev,[11] I. Larin,[11] V. Matveev,[11] V. Tarasov,[11] F. Barbosa,[12] E. Chudakov,[12] M. Dalton,[12] A. Deur,[12] J. Dudek,[12] H. Egiyan,[12] S. Furletov,[12] M. Ito,[12] D. Mack,[12] D. Lawrence,[12] M. McCaughan,[12] M. Pennington,[12] L. Pentchev,[12] Y. Qiang,[12] E. Smith,[12] A. Somov,[12] S. Taylor,[12] T. Whitlatch,[12] B. Zihlmann,[12]

Science case for JLab CLAS12 expt (approved)

Studies of Nucleon Resonance Structure in Exclusive Meson Electroproduction

I. G. Aznauryan,[1,2] A. Bashir,[3] V. M. Braun,[4] S. J. Brodsky,[5,6] V. D. Burkert,[2] L. Chang,[7,8] Ch. Chen,[7,9,10] B. El-Bennich,[11,12] I. C. Cloët,[7,13] P. L. Cole,[14] R. G. Edwards,[2] G. V. Fedotov,[15,16] M. M. Giannini,[17,18] R. W. Gothe,[15] F. Gross,[2,19] Huey-Wen Lin,[20] P. Kroll,[21,4] T.-S. H. Lee,[7] W. Melnitchouk,[2] V. I. Mokeev,[2,16] M. T. Peña,[22,23] G. Ramalho,[22] C. D. Roberts,[7,10] E. Santopinto,[18] G. F. de Teramond,[24] K. Tsushima,[13,25] and D. J. Wilson[7,26]

Involvement with experimental program

NSAC report prominently features spectroscopy, hadron and nuclear structure projects

Report to the
Nuclear Science Advisory Committee
Implementing the 2007 Long Range Plan
January 31, 2013

Looking towards the future - community

Town Hall report providing input to next NSAC Long Range Plan

Computational Nuclear Physics Meeting
SURA Headquarters, Washington DC, July 14-15, 2014

REPORT

Prepared by the Computational Nuclear Physics Meeting Writing Committee
A. Burrows, J. Carlson, W. Detmold, R. Edwards, R. Furnstahl, F. Karsch, W. Nazarewicz, P. Petreczky, D. Richards, W. Hicks, M.J. Savage.

Recommendations endorsed at Joint Town Meeting on QCD in 2014

- New NSAC report in preparation now…

Looking towards the future - software

Proposals for coordinated software development for next generation Leadership Computing Facilities

NERSC: Chroma Lattice QCD Code Suite, Balint Joo (Jefferson National Accelerator Facility)

Oak Ridge:

Center for Accelerated Application Readiness: Preparing USQCD Lattice Gauge Theory Codes for Readiness on Summit

Primary PI: Robert G. Edwards
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Michael A. Clark
NVIDIA Corporation
Email: mclark@nvidia.com
Phone: (617) 820-4824

Argonne: The Hadronic Contribution to the Anomalous Magnetic Moment of the Muon
Co-PI: Balint Joo (porting Chroma to "Theta" at ANL)

Looking towards the future - science program

- Spectroscopy
  - Suggests rich spectrum of mesons & baryons - exotic & non-exotic hybrids
  - Next phase:
    - multi-meson (3 or more) scattering
    - tackle two-quark exotics & scalar sector
    - tetra-quarks - charm, strange, then light
    - N* and strange-baryon spectrum and decays

- Hadron structure
  - First calculations at phys. pion mass of isovector quantities - charge radius, moments…
  - Next phase:
    - direct calculation of isoscalar quantities - resolve proton charge radius “puzzle”
    - full decomposition of spin from quarks and glue - relevant for 12GeV
    - direct determination of quark distributions from pseudo-distributions (Ji’s method)
    - structure of excited states gives insight into glue distribution - relevant to EIC

- Nuclear structure
  - First predictions for larger nuclei through matching to nuclear EFT
  - Next phase:
    - multi-neutron systems and three-body forces
    - axial couplings for neutrino interactions & refinement of double beta-decay rates

Looking towards the future - resources

- Ambitious program - however, constrained by available computational and manpower resources

- Increase in computing resources:
  - Coordination via NSAC process
  - Regain lost share in USQCD facilities funding
  - NSF

- Increase in manpower resources
  - SciDAC - computational expertise
  - Recognize that S-matrix formalism & phenomenology increasingly important
    - DOE Topical collaborations
    - More collaborations in phenomenology
  - NSF

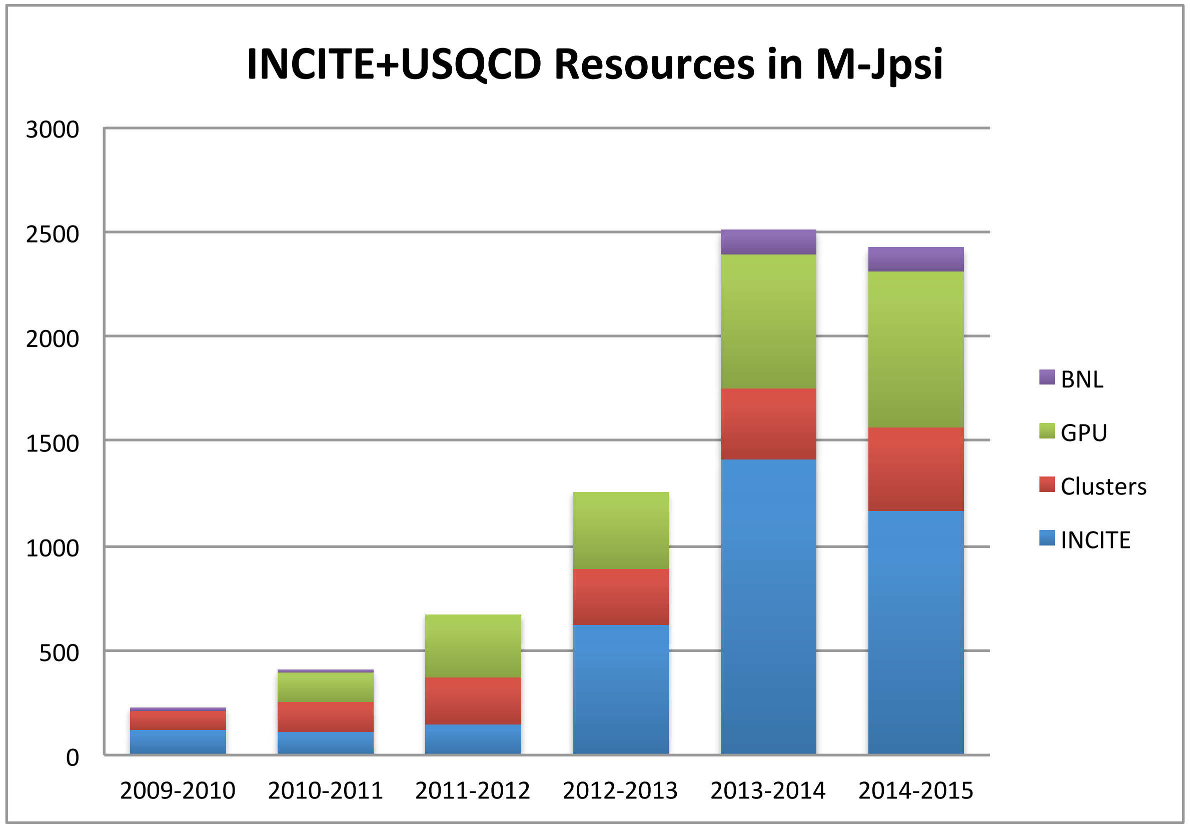
Backup slides

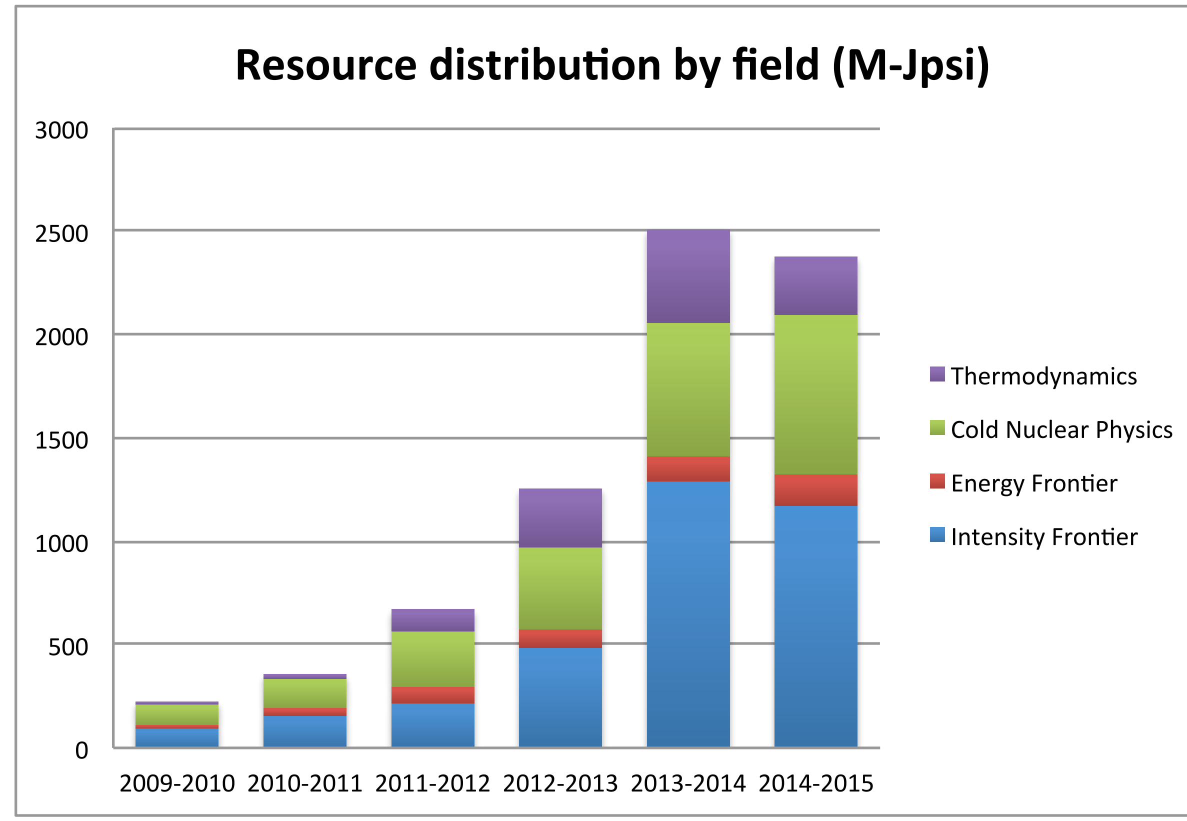
USQCD + INCITE computing resources

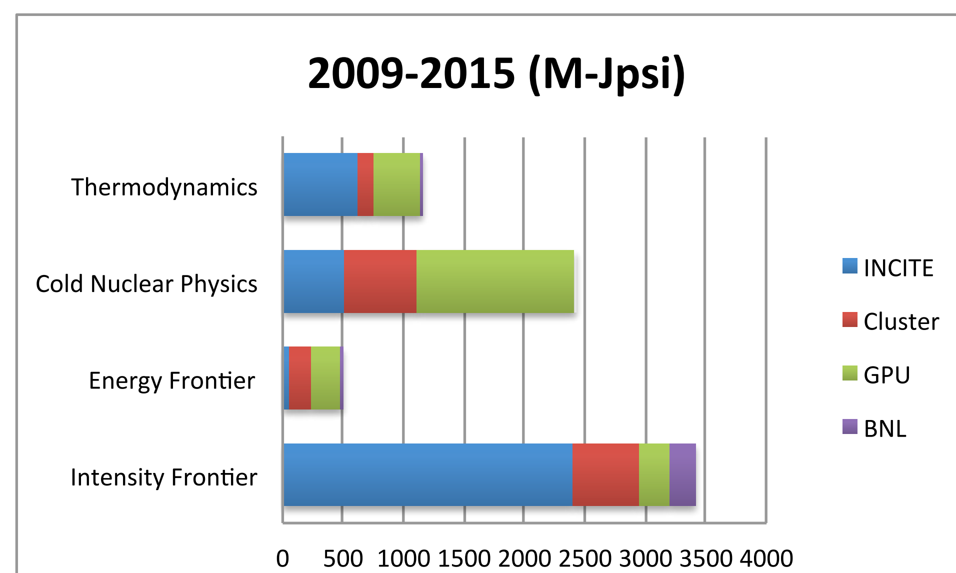
Comparison of computing resources available to USQCD (in Million core-hours)

Normalize by LQCD performance over different machines/performances

A "JPsi" is a unit based on a ~2010 CPU architecture with 100M Jpsi core-hours = 14 TF-yr



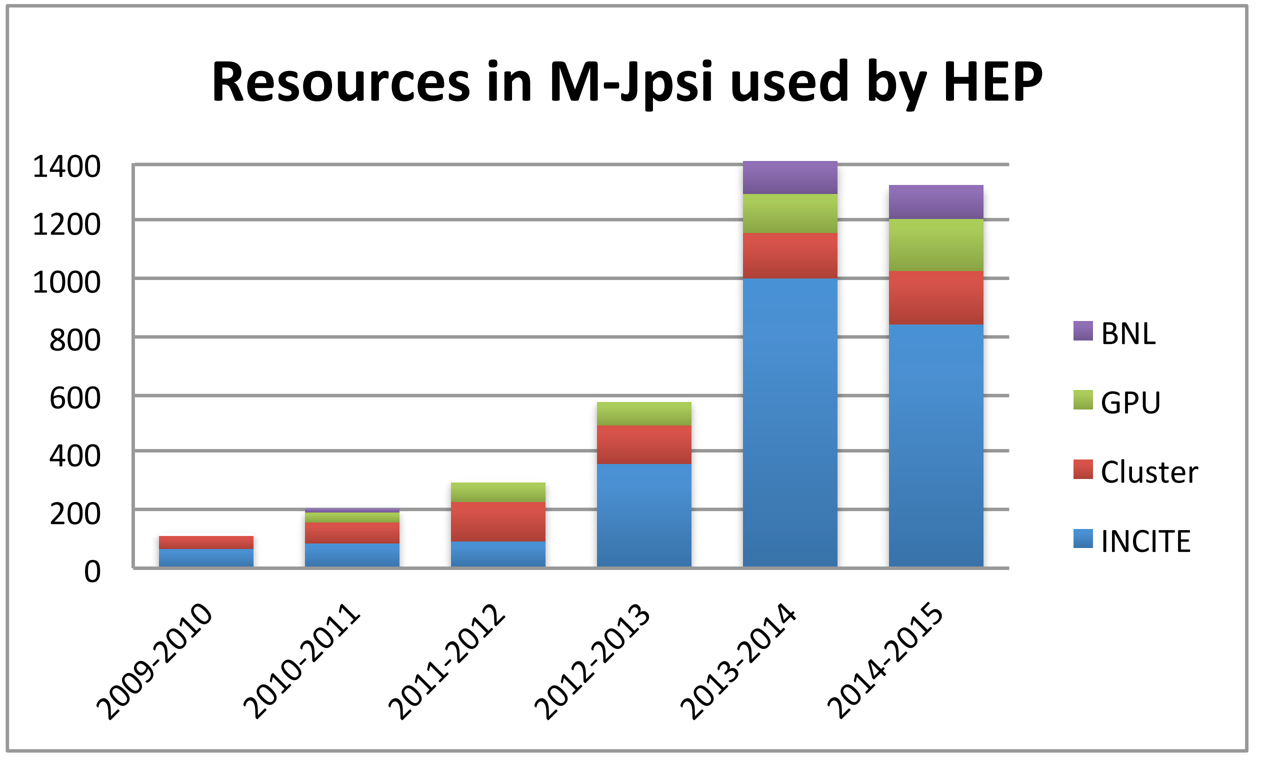


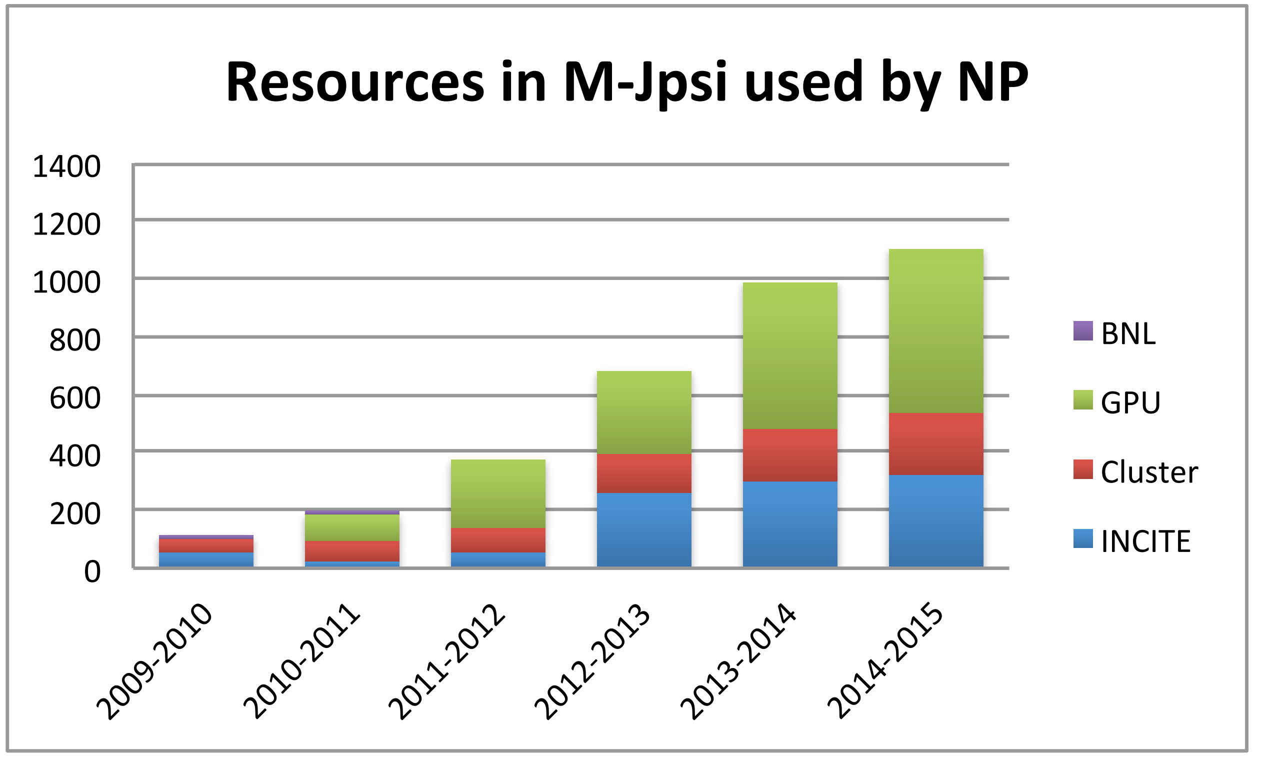


USQCD + INCITE computing resources

Comparison of computing resources available to USQCD (in Million core-hours)

NP receives the majority of its flops from USQCD resources





Excited states from correlators

- How to get at excited QCD eigenstates ?
  - optimal operator for state $|\mathfrak{n}\rangle$ $\Omega^\dagger_{\mathfrak{n}} \sim \sum_i v_i^{(\mathfrak{n})} \mathcal{O}_i^\dagger$

    for a basis of meson operators $\{\mathcal{O}_i\}$

  - can be obtained (in a variational sense) from the matrix of correlators

$$C_{ij}(t) = \langle 0 | \mathcal{O}_i(t)\, \mathcal{O}_j^\dagger(0) | 0 \rangle$$

  - by solving a generalized eigenvalue problem

'diagonalize the correlation matrix'

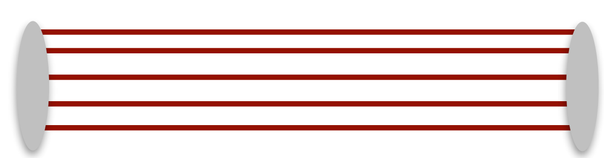
$$C(t) v^{(\mathfrak{n})} = C(t_0) v^{(\mathfrak{n})} \lambda_{\mathfrak{n}}(t)$$

eigenvalues $\lambda_{\mathfrak{n}}(t) \sim e^{-E_{\mathfrak{n}}(t-t_0)}$

  - a large basis can be constructed using covariant derivatives :

$$\mathcal{O} \sim \bar{\psi} \Gamma \overleftrightarrow{D} \ldots \overleftrightarrow{D} \psi$$

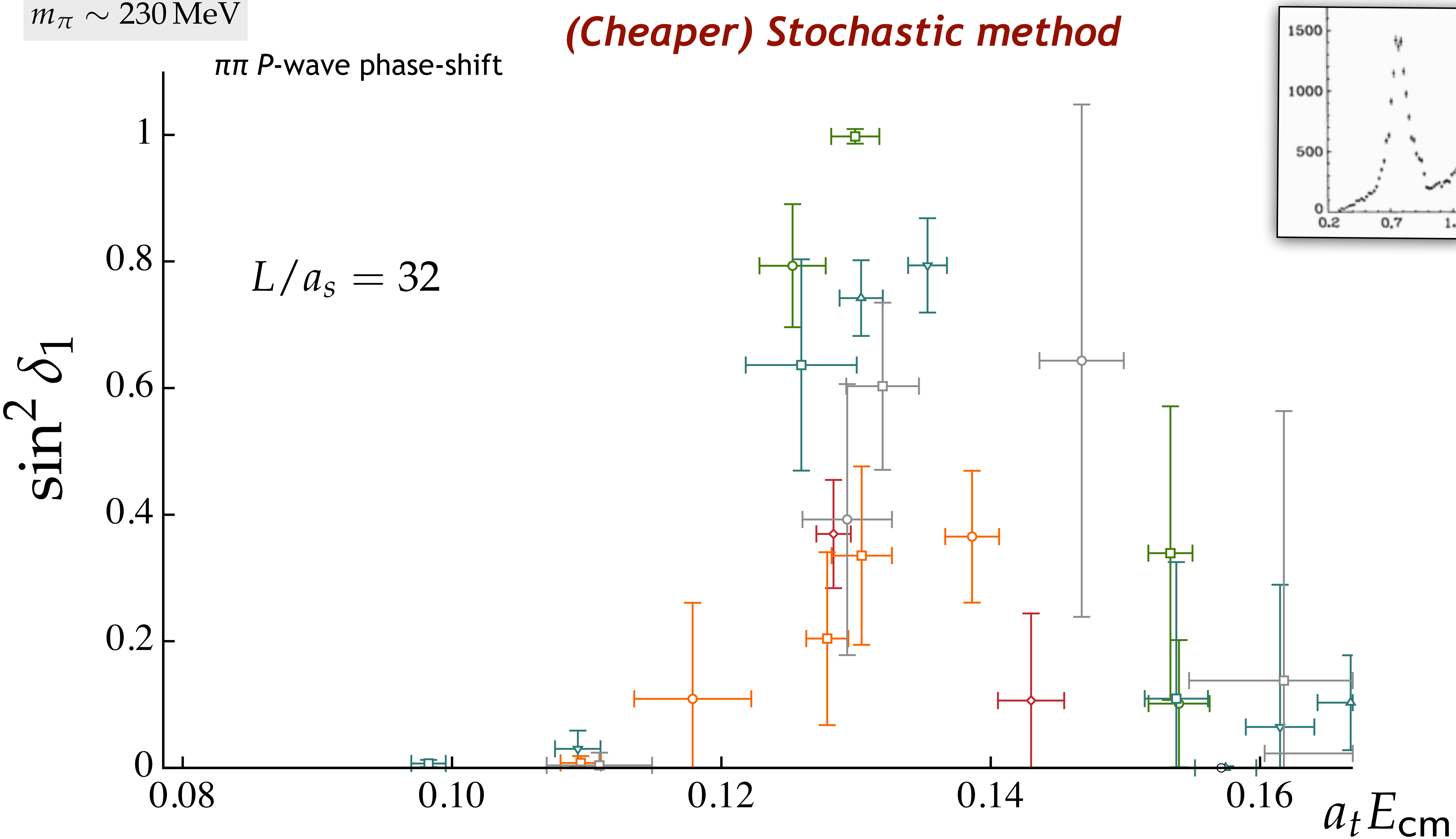
Contraction costs - 2015

	T — $t = 0$		Cost: $N \propto$ Volume	*Assuming dense tensors*
Meson spectroscopy				
meson		$\mathrm{tr}\left(MPMP\right)$	$\sim N^3$	easy
meson-meson			orientations $\sim 100 \times N^3$	affordable
tetraquark			$\sim N^5$	sparse in spin, but not really affordable
Hadron structure				
baryon			$\sim N^4$	affordable
Baryon spectroscopy				
baryon-meson			$\sim 100 \times N^4$	to do a decent job, not affordable
pentaquark			$\sim N^6$	prohibitive

ρ resonance - a comparison of techniques

$m_\pi \sim 230\,\mathrm{MeV}$

(Cheaper) Stochastic method

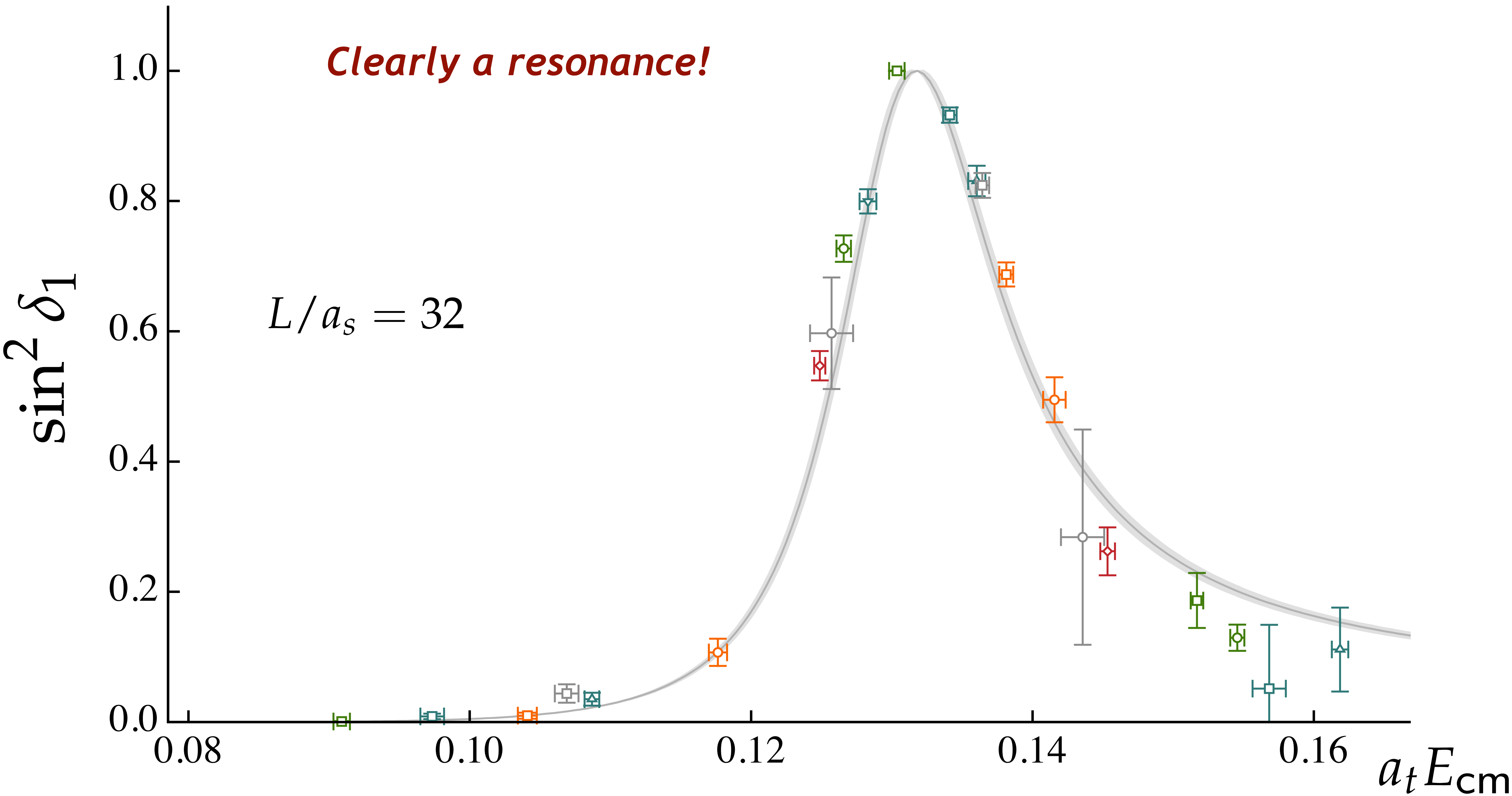


Fahy, et.al. arXiv:1410.8843

Result of ALCC

$m_\pi \sim 230\,\mathrm{MeV}$

Full distillation method

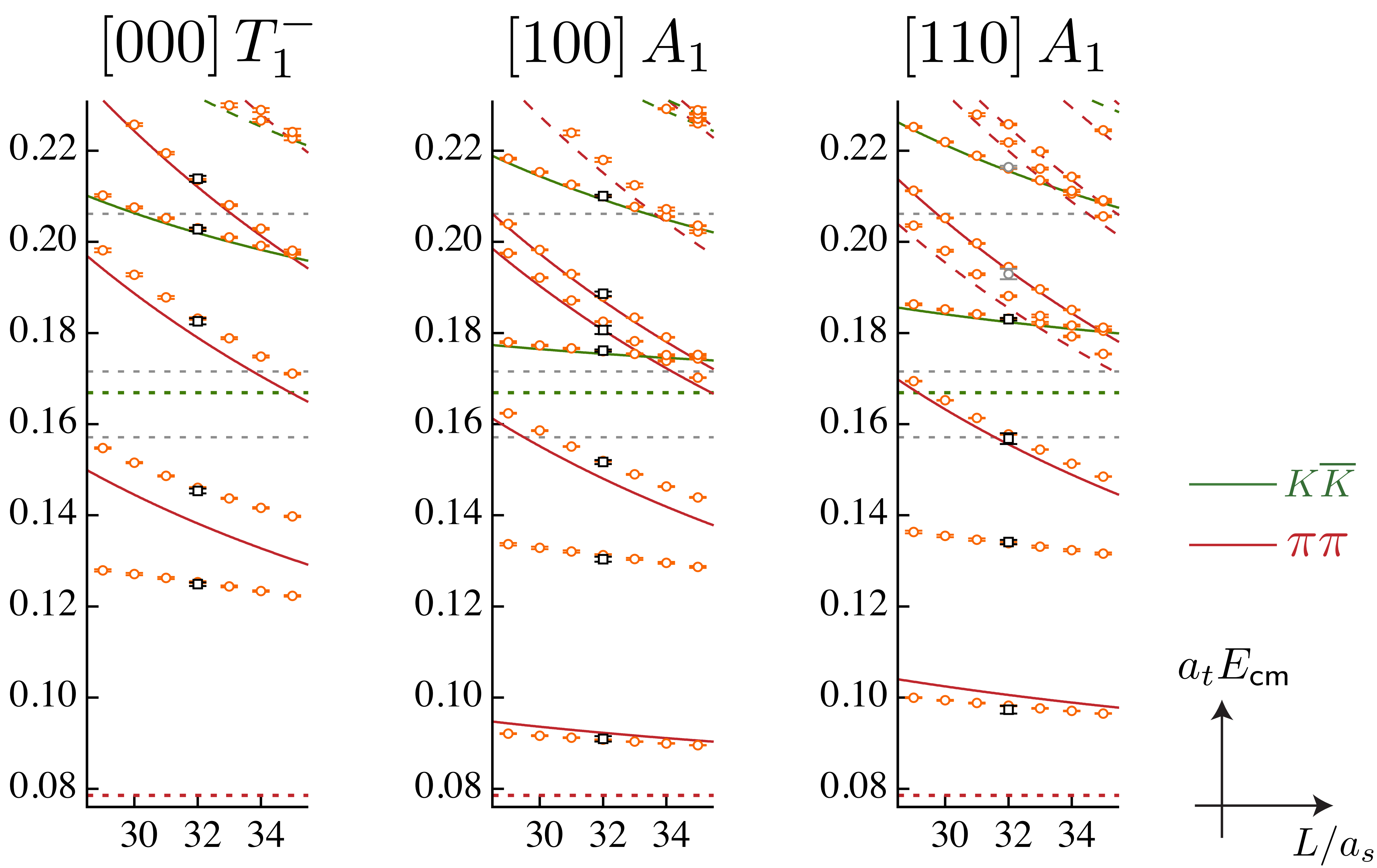


HadSpec: 1507.02599

$\pi\pi/KK$ scattering - “ρ”

- Data points (black) compared to parameterization (gold)

$m_\pi \sim 236$ MeV



HadSpec: 1507.02599

ηπ/KK scattering - "a0"

- Precision (< 1%) essential in constraining scattering levels

$m_\pi \sim 391\,\mathrm{MeV}$